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DIFFERENTIAL CROSS SECTIONS OF THE $Be^9(d,n)B^{10}$ REACTION

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DIFFERENTIAL CROSS SECTIONS OF THE $Be^9(d,n)B^{10}$ REACTION

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S. G. Buccino and A. B. Smith

Reactor Physics Division

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ABSTRACT

Angular distributions of neutrons from the $Be^9(d,n)B^{10}$ reaction were obtained at deuteron energies of 2.6, 3.0, 3.1, 3.2, and 7.0 MeV by means of pulsed-beam time-of-flight techniques. Absolute measurements of the differential cross sections led to the following states in B^{10} at a deuteron energy of 7.0 MeV: g.s., 0.72, 1.74, 2.15, 3.59, 4.77, 5.11 + 5.16, 5.90, 6.10, 6.35, 6.50, and 6.95 MeV. DWBA and Butler calculations were used to extract ℓ_p values and spectroscopic factors for many of the levels observed.

I. INTRODUCTION

In the course of a study of neutron-producing reactions[1] induced by deuterons, the reaction $Be^9(d,n)B^{10}$ was of particular interest. The high Q value (+4.362 MeV) and the presence of several relatively intense neutron groups[1-5] argued strongly for the use of this reaction as a neutron source for transmission studies in the region of 6-11 MeV. An investigation of this reaction might also lead to a better understanding of the structure of the residual B^{10} nucleus. Several reactions have been used to study the states in B^{10}, e.g., $Li^6(\alpha,\gamma)B^{10}$, $Be^9(d,n)B^{10}$, and $B^{10}(p,p')B^{10}$, but the conclusions reached, particularly for states near an excitation energy of 5.1 MeV are not in agreement.[3,4,6,7] In addition, previous work on the $Be^9(d,n)B^{10}$ reaction has been largely confined to low bombarding energies and often employed coarse resolution.

II. EXPERIMENTAL PROCEDURE

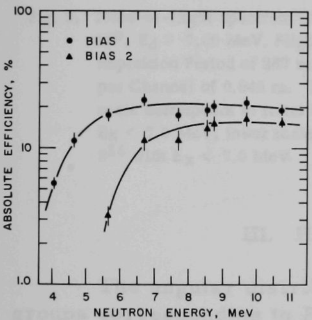
The low-energy measurements (deuteron energies between 2.6 and 3.2 MeV) were made with the 3-MeV Van de Graaff facility,[8] which can provide high-intensity (peak current ≤8 mA) beam bursts of ~1-ns duration. The 7.0-MeV data was obtained with the use of the ANL tandem Van de Graff. The latter is equipped with a pulsed-beam system[9] based on a University of Wisconsin design[10] which delivers a 1-ns beam burst with peak currents of ≤25 μA.

The targets consisted of thin (10-50 keV) films of beryllium metal which had been evaporated onto a 10-mil platinum or tantalum backing.

The neutron detector consisted of a liquid organic scintillator (NE 213), 5 cm thick by 20 cm in diameter, coupled to a 58-AVP photomultiplier. Signals from the photomultiplier were fed directly to a CDC 160A[11] computer which performed a two-dimensional analysis of the data, i.e., energy loss in the scintillator vs time of flight.

In order to obtain absolute cross sections, the target thickness and neutron efficiency must be known. The former was obtained from a chemical analysis of the targets after completion of the experiment.*

The efficiency of the detector for the 7.0-MeV measurements was determined by means of the $D(d,n)He^3$ reaction. A cell containing deuterium gas was bombarded with 8.15- and 5.80-MeV deuterons, and the emerging neutrons were observed at 10 angles between 16 and 95°, a region where the angular distribution is not changing violently with angle. By use of the reported[12] values of the differential cross sections at these energies, the measured collected charge, and gas pressure, the absolute efficiency of the detector was obtained. The calibration results are shown in Fig. 1 for two different bias levels. Estimated errors are about 10-15%.



112-5467

Fig. 1. Absolute Efficiency Curve at Two Different Energy Biases

Measurements for the $Be^9(d,n)B^{10}$ reaction were made at 15 angles from 2.5 to 75° and at flight paths of 7 to 15 m. Figure 2 shows a representative time-of-flight spectrum at E_d = 7.00 MeV, θ = 15°, and a flight path of 14.7 m. This curve indicates the complex structure observed when the bias level is low, i.e., with good neutron sensitivity. Figure 3 illustrates the best available resolution (~15 keV) at a deuteron energy of 2.6 MeV. The use of an n-γ discrimination circuit helped considerably in reducing the γ-ray background in these studies.[8]

No attempt was made to determine the differential cross sections at the four lowest energies--the main objective of these data was to determine the shape of the angular distributions for the 5.11- and 5.16-MeV transitions, which could not be resolved at the highest energy, and to search for the reported state of 5.18 MeV.[4,9]

---

*We are indebted to R. Bane of the Chemistry Division, ANL, for analyses of the targets.

The targets consisted of thin (10-50 keV) films of beryllium metal which had been evaporated onto a 10-mil platinum or tantalum backing.

The neutron detector consisted of a liquid organic scintillator (NE 213), 5 cm thick by 20 cm in diameter, coupled to a 58-AVP photomultiplier. Signals from the photomultiplier were fed directly to a CDC 160A[11] computer which performed a two-dimensional analysis of the data, i.e., energy loss in the scintillator vs time of flight.

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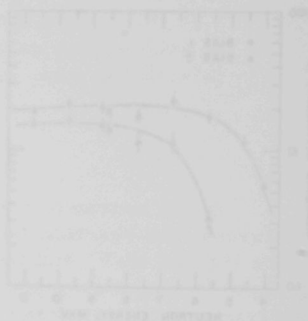
The efficiency of the detector for the 7.0-MeV measurements was determined by means of the $D(d,n)He^3$ reaction. A cell containing deuterium gas was bombarded with 8.15- and 9.80-MeV deuterons, and the emerging neutrons were observed at 10 angles between 16 and 95°, a region where the angular distribution is not changing violently with angle. By use of the reported[14] values of the differential cross sections at these energies, the measured collected charge, and gas pressure, the absolute efficiency of the detector was obtained. The calibration results are shown in Fig. 1 for two different bias levels. Estimated errors are about 10-15%.



113-3987

Fig. 1. Absolute Efficiency Curve at Two Different Energy Bias

Measurements for the $Be^9(d,n)B^{10}$ reaction were made at 15 angles from 2.5 to 75° and at flight paths of 7 to 15 m. Figure 2 shows a representative time-of-flight spectrum at E_d = 7.00 MeV, θ = 15°, and a flight path of 14.7 m. This curve indicates the complex structure observed when the bias level is low, i.e., with good neutron sensitivity. Figure 3 illustrates the best available resolution (~15 keV) at a deuteron energy of 2.6 MeV. The use of an n-γ discrimination circuit helped considerably in reducing the γ-ray background in these studies.[6]

No attempt was made to determine the differential cross sections at the four lowest energies--the main objective of these data was to determine the shape of the angular distributions for the 5.11- and 5.16-MeV transitions, which could not be resolved at the highest energy, and to search for the reported state of 5.18 MeV.[4,7]

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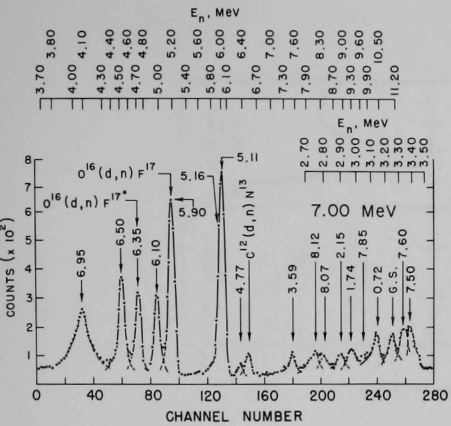
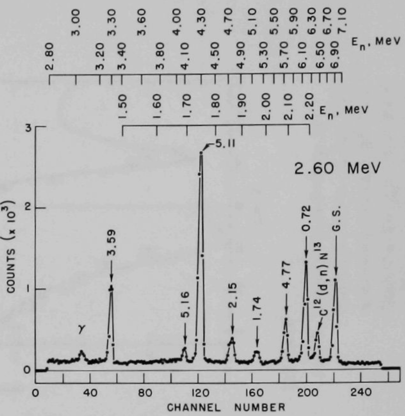


112-4835

Fig. 2. Time-of-flight Spectrum Obtained at θ = 15°, E_d = 7.00 MeV, Flight Path = 14.7 m, Repetition Period of 267 ns, and a Time per Channel of 0.945 ns. Upper energy scale corresponds to states in B^{10} with E_x < 7.0 MeV; lower scale to states in B^{10} with E_x < 7.0 MeV.



112-4836

Fig. 3. Time-of-flight Spectrum Obtained at θ = 10°, E_d = 2.60 MeV, Flight Path = 18.6 m, Repetition Period of 300 ns, and a Time per Channel of 1.39 ns. Upper energy scale corresponds to states in B^{10} with E_x < 4.7 MeV; the lower scale to high-lying states (E_x < 4.7 MeV).

III. EXPERIMENTAL RESULTS

The angular distributions at E_d = 7.0 MeV for all resolved neutron groups corresponding to $E_x \leq$ 6.95 MeV are shown in Figs. 4-6. The absolute uncertainty was judged to be ±30%. The solid curves are the result of a DWBA calculation[13] with the indicated ℓ_p values and the following potentials:

a) Neutron[14]

$$U(r) = Vf(r) - iWg(r);$$

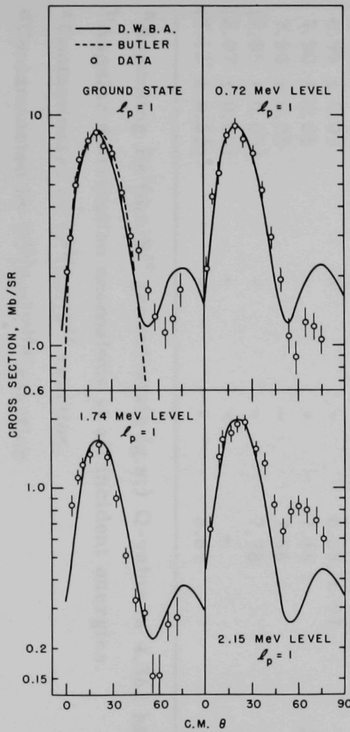
$$f(r) = \left[1 + \exp\frac{r - R}{a}\right]^{-1}; \quad g(r) = \exp\left[-\left(\frac{r - R}{b}\right)^2\right];$$

$R = r_0 A^{1/3}$; $\qquad V$ = 42.36 MeV;

r_0 = 1.35 F; $\qquad W$ = 9.44 MeV;

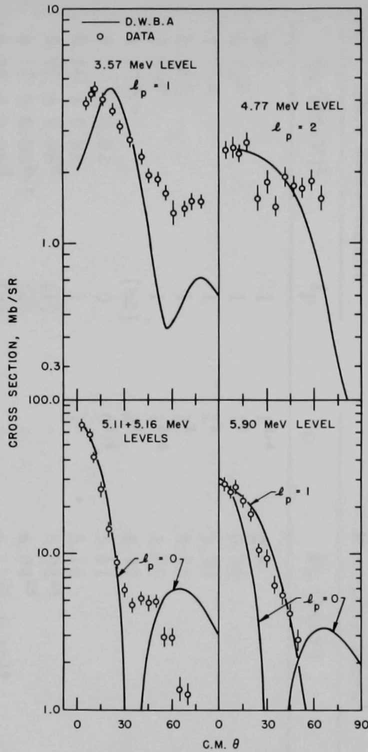
a = 0.55 F;

b = 0.75 F;



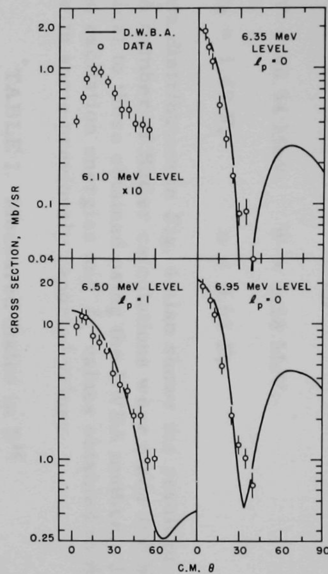
112-5135

Fig. 4. Angular Distributions at E_d = 7.0 MeV for the Ground and First Three Excited States of B^{10}. Solid lines are the results of DWBA calculations; dotted line is result of a Butler plan-wave calculation.



112-5470

Fig. 5. Angular Distributions of the 3.57-, 4.77-, 5.11 + 5.16-, and 5.90-MeV Levels in B^{10} at a Deuteron Energy of 7.0 MeV. Solid lines are the results of DWBA calculations



112-5468

Fig. 6. Angular Distributions of the 6.10-, 6.35-, 6.50-, and 6.95-MeV Levels in B^{10} at a Deuteron Energy of 7.0 MeV. Solid lines are the results of DWBA calculations

b) Deutron[15]

$$U(r) = -(V + iW)\, f(r) + Vc(r);$$

$$V = 40.34 \text{ MeV}; \quad W = 6.58 \text{ MeV};$$

$$r_0 = 1.49 \text{ F}; \quad a = 0.63 \text{ F};$$

The ground-state distribution in Fig. 4 also shows the result of a Butler calculation.[16] A number of Butler calculations were made and resulted in ℓ_p values identical to those obtained using the DWBA method. Table I summarizes the excitation energies and ℓ_p values obtained in the present work together with some previously reported values.

TABLE I. Measured States in B^{10}

This Experiment		Previous Work[f]		
E_x (MeV)[a]	ℓ_p	ℓ_p	E_x (MeV)	J^π
g.s.	1	1[2,4]	g.s.	3^+
0.72[e]	1	1[2]	0.72	1^+
1.74[e]	1	1[2]	1.74	0^+
2.15[e]	1	1[2]	2.15	1^+
3.59[e]	1	1[2,4]	3.59	2^+
4.77[b,e]	(≥2)	2[4]	4.77	(2^+)
5.11 ± 0.02	0	0[3,4]	5.11	(2^-)
5.16 ± 0.02	1	1[3]	5.16	(2^+)
5.90 ± 0.08[c]	(1)	-	5.92[25]	2^+
6.10 ± 0.08[b,c]	(2)	-	6.04[25]	4^+
6.35 ± 0.05[d]	(0)	-	6.12[25], 6.40[19]	
6.50 ± 0.05	1	-	6.57[25]	
6.95 ± 0.03	0	-	6.88, 6.97	1-
7.50 ± 0.05	-	-	7.48	2^+, 2^-
7.60 ± 0.05	-	-	7.56	0^+
(7.85 ± 0.05)	-	-	7.78	2^-
(8.07 ± 0.05)	-	-	-	-
(8.12 ± 0.05)	-	-	8.89	3^-

[a]Assuming $Be^9(d,n)B^{10}$ ground-state (g.s.) Q-value is 4.362 MeV.

[b]Angular distribution anomalous at all incident energies.

[c]Contaminated by $O^{16}(d,n)F^{17}$ reaction.

[d]Contaminated by $O^{16}(d,n)F^{17*}$ reaction.

[e]The excitation energies of these levels were taken from Ref. 18.

[f]Where not otherwise noted, reference is to Ref. 18.

A comparison of the differential cross sections obtained at 7.0 MeV with the DWBA calculations provided the spectroscopic factors listed in Table II. This table gives both the absolute spectroscopic factors and values relative to that of the ground-state transition. The previously reported quantities are in reasonable agreement with those obtained in this experiment except for the factor pertaining to the excitation of the 1.75-MeV state.[2,17]

TABLE II. Spectroscopic Factors for the Be^9(d,n) Reaction

	Present Results (E_d = 7.0 MeV)		Previous Work	
Level (MeV)	Absolute Spectroscopic Factors	Relative Spectroscopic Factors	Relative Spectroscopic Factors, Ref. 17 $Be^9(He^3,d)B^{10}$, E = 5.7 MeV	Relative Spectroscopic Factors, Ref. 26 $Be^9(d,n)B^{10}$, E = 2.8 MeV
g.s.	0.49	1.0	1.0	1.0
0.72	1.12	2.3	2.1	2.24
1.74	0.50	1.0	3.9	0.85
2.15	0.20	0.41	0.87	0.60
3.59	0.22	0.45	-	0.32
4.77	0.21	0.43	-	-
5.11[a]	0.64	1.3	-	-
5.90	0.66	1.3	-	-
6.35[b]	(0.42), 0.25	(0.86), 0.51	-	-
6.95	0.90	1.8		

[a]Contains small (<5%) contribution from the 5.16-MeV level.

[b]Values in parentheses assume J = 1; others are results assuming J = 2.

Table III lists the differential cross sections obtained at 7.0 MeV for transitions leading to excited states in B^{10}.

TABLE III. Be^9(d,n) Lab. Differential Cross Sections $\sigma(\theta)$ mb/SR
E_d = 7.00 MeV

$\theta \backslash E_x$	Ground State	0.72	1.74	2.15	3.59	4.77*	5.11, 5.16	5.90**	6.10†	6.35†	6.50	6.95
2.5	-	-	-	-	-	-	91.5	-	5.68	-	-	-
3.7	2.58	2.70	-	0.83	-	3.30	90.0	38.8	-	25.8	13.7	27.3
5	3.63	2.75	1.05	-	5.15	-	-	-	-	19.8	-	-
8	6.13	5.50	1.40	1.33	5.60	3.38	78.5	34.5	8.50	15.0	16.2	21.6
11	7.88	6.95	1.58	2.03	5.80	3.18	56.8	36.5	11.6	7.43	14.4	16.9
16	9.50	10.1	1.73	2.13	5.33	3.58	34.8	30.3	13.4	3.95	11.4	7.03
20	10.25	11.0	1.90	2.33	4.68	2.05	18.9	24.8	12.8	2.15	10.2	3.05
25	8.88	9.50	1.65	2.38	4.03	2.40	11.5	13.8	10.7	1.15	8.70	1.80
30	8.25	8.25	1.08	1.80	3.50	1.83	7.48	12.5	8.65	1.15	5.85	1.45
35	5.50	5.63	0.60	1.53	2.90	2.40	5.98	8.25	6.48	0.50	4.80	0.90
40	3.50	3.50	0.38	1.00	2.38	2.18	6.48	7.00	6.35	0.25	4.20	0.28
45	3.00	2.25	0.33	0.75	2.25	2.10	5.98	5.25	4.93	-	2.70	-
51	2.00	1.25	0.18	0.90	1.93	2.23	5.98	3.50	4.73	-	2.70	-
55	1.50	1.00	0.18	0.93	1.58	1.83	3.48	1.88	4.18	-	1.20	-
60	1.25	1.38	0.28	0.88	1.60	-	3.38	-	-	-	1.20	-
65	1.38	1.30	0.30	0.78	1.70	-	1.50	-	-	-	-	-
70	1.88	1.13	-	0.63	1.63	-	1.38	-	-	-	-	-

*Contains some $C^{12}(d,n)N^{13}$.

**Contains unknown contribution from the $O^{16}(d,n)F^{17}$.

†Contains unknown contribution from the $O^{16}(d,n)F^{17*}$.

A comparison of the differential cross sections obtained at 7.0 MeV with the DWBA calculations provided the spectroscopic factors listed in Table II. This table gives both the absolute spectroscopic factors and values relative to that of the ground-state transition. The previously reported quantities are in reasonable agreement with those obtained in this experiment except for the factor pertaining to the excitation of the 1.74-MeV state.

TABLE II. Spectroscopic Factors for [illegible] Reaction

	Present Results (E_d = 7.0 MeV)		Previous Work		
Ex (MeV)	Absolute Spectroscopic Factors	Relative Spectroscopic Factors	[illegible]	[illegible]	Relative Spectroscopic Factors
[illegible]	0.[illegible]	1.0	[illegible]	[illegible]	1.0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	0.[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	(0.[illegible]) 0.45	(0.86) [illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[a] Includes small [illegible] contribution [illegible] level.

[b] Values in parentheses are [illegible] results assuming l = 1.

Table III lists the differential cross sections obtained at 7.0 MeV for transitions leading to excited states in B^{10}.

TABLE III. [illegible] Differential Cross Sections [illegible] mb/sr [illegible] MeV

θ	Ground State	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

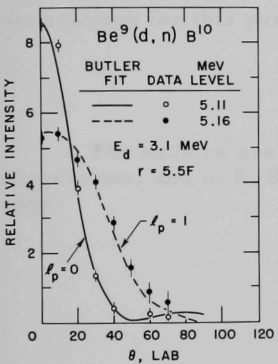
[illegible]

[illegible]

IV. DISCUSSION

B^{10} lies near the midpoint of the 1p-shell. Its structure is remarkably well described by the intermediate coupling model of D. Kurath,[20] which predicts excitations and configurations for the first five states in nearly quantitative agreement with this experiment. This model predicts $T = 1$ states at ~1.7 (0^+) and ~5.1 (2^+) MeV. The former probably corresponds to the observed 1.74 MeV state.

There has existed some confusion on the ~5.1-MeV state. Three levels in this region have been previously reported at 5.11, 5.16, and 5.18 MeV. This work indicates the presence of only the 5.11- and 5.16-MeV states. Butler fits to the angular distributions (Fig. 7) lead to the assignments of $\ell_p = 0$ and $\ell_p = 1$, respectively, for the 5.11- and 5.16-MeV transitions, in agreement with the results of Riley et al.[3] The positive-parity 5.16-MeV level is probably the state predicted by Kurath. Warburton and Chase[21] have suggested that the reported 5.18-MeV state may belong to a doubly excited configuration which should not be excited by single-nucleon direct excitations, such as the $Be^9(d,n)B^{10}$ reaction. Ferguson et al.,[4] however, report the level in their (d,n) studies. The present experiments would indicate that the state, if excited at all, would have a yield only 10% of that from the 5.16-MeV state, which is itself quite small. The observed 5.11-MeV state must have $J^\pi = 1^-$ or 2^-, contradicting the results of $Li^6(\alpha,\gamma)B^{10}$ studies[7] which suggest an assignment of 2^+ or 4^-. The present results are, however, compatible with the results of Refs. 3 and 9.



112-5477

Fig. 7. Angular Distributions of the 5.11- and 5.16-MeV Levels in B^{10} at a Deuteron Energy of 3.1 MeV. Solid and dotted lines are the result of Butler plane-wave calculations. The data for the two levels are drawn on different scales.

The observed level at 4.77 MeV is an enigma. Kurath's model would require a two-neutron excitation if this level is 1^+ as previously suggested,[23] an indication that this level is probably not appreciably excited by one-particle stripping. The present work indicates that $\ell_p \geq 2$, a result which does not contradict a recent theoretical estimate[22] of 3^+.

A previously reported state at 5.58 MeV[24] was not observed. This may be partly due to the presence of oxygen in the beryllium targets. The reactions $O^{16}(d,n)F^{17}$ and $O^{16}(d,n)F^{17*}$ tend to confuse the observation of states in B^{10} at excitation energies of 5.5 to 6.5 MeV.

The reported 5.9-MeV state in B^{10} was observed and qualitative angular distributions obtained despite the oxygen contamination. An observed

IV. DISCUSSION

B^{10} lies near the midpoint of the 1p shell. Its structure is reasonably well described by the intermediate-coupling model of D. Kurath,[20] which predicts excitations and configurations for the first five states in nearly quantitative agreement with this experiment. This model predicts $T = 1$ states at [illegible] and [illegible] MeV. The latter apparently corresponds to the observed [illegible] MeV state.

There has existed some confusion on the [illegible]-MeV state. Three levels in this region have been previously reported at 5.11, 5.16, and 5.18 MeV. This work indicates the presence of only the 5.11- and 5.16-MeV states. Butler fits to the angular distributions (Fig. 7) lead to the assignments of $\ell_p = 0$ and $\ell_p = 1$, respectively, for the 5.11- and 5.16-MeV transitions, in agreement with the results of Riley et al. The positive-parity 5.1-MeV level is probably the state predicted by Kurath. Warburton and Chase[?] have suggested that the reported 5.18-MeV state may belong to a doubly excited configuration which should not be excited by single-nucleon direct excitations, such as the $Be^9(d,n)B^{10}$ reaction. Ferguson et al.[?] now even report the level in their (d,n) studies. The present experiments would indicate that the state, if excited at all, would have a yield only [illegible] of that from the 5.16-MeV state, which is itself quite small. The observed 5.[illegible]-MeV state must have $J^\pi = 1^+$ or 2^+, contradicting the results of $Li^6(\alpha,\gamma)B^{10}$ studies,[?] which suggest an assignment of 2^- or 1^-. The present results are, however, compatible with the results of Refs. 3 and [illegible].

MU-[illegible]

Fig. 7. Angular distributions of the 5.11- and 5.16-MeV levels in B^{10} at a deuteron energy of 9.1 MeV. Solid and dotted lines are the results of Butler calculations. The [illegible] for the two levels are [illegible] different scales.

The observed level at 4.77 MeV is intriguing. Kurath's model would require a two-nucleon excitation if this level is 1^+ as previously suggested.[22] an indication that this level is probably not appreciably excited by one-particle stripping. The present work indicates that ℓ_p [illegible], a result which does not contradict [illegible] of theoretical estimate[22] of [illegible].

A previously reported state at 5.92 MeV[?] was not observed. This may be partly due to the presence of oxygen in the [illegible] targets. The reactions $O^{16}(d,n)F^{17}$ and $O^{16}(d,n)F^{17}$ tend to obscure the observation of states in B^{10} at excitation energies of [illegible] to [illegible] MeV.

The reported 6.0-MeV state in B^{10} was observed and qualitative angular distributions obtained despite the oxygen contamination. An observed intense neutron group was attributed to the excitation of a 6.10 ± 0.08 MeV state in B^{10}. This group was probably due to the composite excitation of reported 6.05- and 6.16-MeV levels.[4,25] Neutron groups corresponding to states in B^{10} at 6.50 and 6.35 MeV were clearly observed. The latter is at least partially due to the reaction $O^{16}(d,n)F^{17*}$ and the former has been previously reported.[5] A broad state ($\Gamma \sim 200$ keV) was seen at 6.95 MeV, probably corresponding to the known level in B^{10} at 7.00 MeV.[25] Five additional states were observed, all with $E_x > 7.0$ MeV. None of these were appreciably excited by the (d,n) reaction.

V. CONCLUSION

The results of the present work indicate that neutron yields from the $Be^9(d,n)B^{10}$ reaction are in general sufficient for transmission studies in the range from 6 to 11 MeV. The reaction can also be used as a convenient calibration source to determine the absolute efficiency of time-of-flight spectrometers. Subsequent work[27] at this laboratory has indeed used the reaction for this purpose with good results.

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intense neutron group was attributed to the excitation of a 6.10 ± 0.05 MeV state in B^{10}. This group was probably due to the composite excitation of reported 5.92 and 6.16-MeV levels. [illegible] neutron groups corresponding to states in B^{10} at [illegible] and 6.?5 MeV were clearly observed. The latter is at least partially due to the reaction [illegible] (d,n) [illegible] has been previously reported. A broad state [illegible] was [illegible] 9.95 MeV, probably corresponding to the known level [illegible]. Five additional states were observed, all with E [illegible] were appreciably excited by the (d,n) reaction.

CONCLUSIONS

The results of th[illegible] neutron groups from the $Be^9(d,n)B^{10}$ reaction are [illegible] sufficient for extensive studies in the range from 6 to 11 MeV. [illegible] a convenient calibration source to d[illegible] time-of-flight spectrometers. Subsequent[illegible] used the reaction for this purpose [illegible].

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